PATENT SPECIFICATION

(19)

(54) SYNCHRONOUS LINEAR ELECTRIC MOTOR

(71) We, UNIVERSITY COLLEGE OF NORTH WALES, a British University College, of Bangor, North Wales, do hereby declare the invention, for which we pray
5 that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The invention relates to a linear electric
10 motor for giving accurately controllable linear displacements.

For very accurate linear displacement control it is common at the present time to employ a rotating motor which drives a
15 mechanical arrangement such as a lead screw for converting the motion to a linear motion. Such systems have severe disadvantages because of mechanical backlash. Hydraulic drive systems are used for giving
20 linear motion but suffer from limitations as to available stroke for a given accuracy. Because of the above reasons it is customary for high accuracy movement control to employ a closed-loop control system in
25 which the drive is controlled in such a way as to reduce an error signal representative of the difference between a displacement command signal and a feedback signal from a position sensor. Such closed-loop systems
30 tend to reduce the effects of electrical and mechanical back-lash but require accurate sensors and electronic equipment. It is an object of the present invention to provide an improved accurate linear drive motor which
35 will overcome at least some of the above disadvantages.

According to the invention there is provided a linear electric motor comprising a first cylindrical member provided with
40 windings which may be energised to produce a magnetic field perpendicular to the longitudinal axis of the member and controllable in direction, and a second cylindrical member inside or outside the
45 first member; there being an air-gap between the members and the members being axially movable with respect to each other, one of the members having a magnetically salient helix and the other member having, in axial section, magnetic projections adjacent 50 the helix, which projections follow a path or paths on the second member, the arrangement being such that the path or paths and the helix cross so that the spacing between the projections and the helix varies 55 around the air-gap and is least at points along one or more pairs of diametrically opposed generators (as herein defined), the positions of which generators depend on the relative axial positions of the members. 60

As used herein "generator" means a line in the air-gap parallel to the said axis.

"Helix" includes a multiple-start helix which can be regarded as two or more parallel helices. 65

In use, one of the members will be fixed as a stator and the other member will be movable and can be regarded as the armature. Either the inner or the outer member can be the stator and the field 70 windings can be carried by the stator or the armature. Normally, the field windings are carried by the stator and reference will be made hereinafter to "stator field" although it is to be understood that this refers to the 75 field of the wound member, whether fixed or movable.

The stator field permeates the armature and minimum reluctance to the field is presented where the helix and the 80 projections are closest. Thus, there will be a series of minimum reluctance points along the said generators. When the stator field is established in a particular rotational postion there will be a tendency for the members to 85 move axially relative to each other until the direction of the diameter between the said generators coincides with the direction of the stator field. If the stator field is then rotated, further relative axial movement of 90 the members will be induced. It will be seen that linear mechanical movement can be

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derived in this way directly from a rotating field. The field can be supplied by conventional multiphase voltages or may be stepped in discrete rotational increments for a digital type of drive.

The armature may have the helix, the stator may have the helix, or both may have helices as described below, the second helix then constituting the magnetic projections.

The magnetic projections may be constituted by annular ribs separated by annular grooves. With this arrangement it is necessary for the helix to be a two or four start helix, or in general a helix with an even number of starts. The stator field may have two, four, six or even more poles and for optimum efficiency it is desirable to provide a pair of said generators for each pair of poles. Thus it is convenient in a two-pole machine in which the magnetic projections are constituted by annular ribs to provide a two-start helix, in a four-pole machine a four-start helix, and so on.

However, instead of the magnetic projections being constituted by annular ribs they may be constituted by another magnetically salient helix of opposite hand to the first. If the two helices have the same pitch there will be two diametrically opposite generators defining points of minimum reluctance, which generators will move around the axis as the armature advances. This is suitable for a two-pole stator field. If the pitch ratio of the helices is 3:1 there will be four minimum reluctance generators — this being suitable for a four-pole field, and so on. With a contra-helix arrangement, unlike the arrangement in which the projections are annular ribs, it is necessary to ensure that there is no relative rotation allowed between the stator and armature. There will be a tendency for rotation because of the magnetic induction motor effect when the stator field is rotated. If rotation is allowed with the contra-helix arrangement there will be consequent and undesired linear movements. However, relative rotation offers the facility for setting a zero position for the motor, it being possible to turn the armature until the minimum reluctance positions correspond to a datum field position and then lock the armature against further rotation.

With the contra-helix arrangement both helices may be single start or, for multiple pole machines, multiple start of the same pitch.

The helix and/or ribs may be continuous or may be constituted by teeth spaced apart by gaps and disposed with their centres along an annular or helical path, as the case may be. The teeth may be of any shape and if they are rectangular or square their sides may or may not be aligned with the annular or helical direction.

In axial section the salient helix will appear as spaced projections. The salient parts of the members will be referred to as "teeth" hereinafter whether they are in the form of a helix or annular ribs and whether or not the helix and/or ribs are continuous or constituted by discrete teeth.

In a preferred arrangement the teeth are rectangular in axial section and the axial spacing between the teeth is equal to the width of the teeth. There will be an air gap between the teeth of the armature and the teeth of the stator and usually it will be required for optimum efficiency to keep this air gap as small as possible. However, there are limitations. The principal limitation is that it is usually necessary to support the inner member of the two at relatively widely spaced points beyond the ends of the outer member. Therefore there is a tendency for the inner member to be ill-supported between its bearings. Thus there may be a tendency for lateral movement which would change the air gap from place to place. Sufficient clearance must be left for this.

Usually, the pitch of the helix will be determined by the particular characteristics of torque and accuracy required of the motor. Theoretical analysis and experiments have shown that there is an optimum relationship between the spacing gap s of the teeth and the gap g between the armature and stator teeth. Preferably the ration s/g is between 2.5 and 4.

The invention will further be described with reference to the accompanying drawing, of which:—

Figure 1 is a perspective view of the stator of a motor in accordance with the invention;

Figure 2 is a cross-sectional view of the stator of Figure 1 with the windings and the armature in place;

Figure 3 is a diagrammatic illustration of the stator helix and the armature teeth of the motor of Figures 1 and 2; and

Figure 4 is a diagrammatic illustration of an alternative arrangement for the stator and the armature of a motor in accordance with the invention.

Referring to Figures 1 and 2 the motor comprises a cylindrical laminated steel stator 1 having a cylindrical bore 2 to accept a cylindrical armature 3. The stator has twelve winding slots 4 which, in use, are provided with coils 5 which are short-corded by one slot and wired to form a three-phase star-connnected winding. The stator is mounted on bearings (not shown) to move on the armature 3 which is fixed.

The interior of the bore 2 is provided with a two-start helical thread of square cross-section as shown in Figure 2. The helical grooves 6 are of the same width s as the upstanding thread portions 7. The pitch of the helix is $4s$.

The armature 3 is cut with annular grooves 8 to leave upstanding ribs 9. The width of grooves 8 and ribs 9 is each s. Thread portions 7 and ribs 9 are salient teeth and armature teeth respectively herein. Because the helix is a two-start helix the distance from centre to centre of the stator teeth is $2s$. The armature teeth are similarly spaced.

The gap g between the stator teeth and armature teeth is arranged in accordance with the tooth spacing gap s so that the ratio s/g is between 2.5 and 4. The particular choice of ratio within this range will depend upon the application for which the motor is intended but this range represents the optimum value for the ratio.

The stator windings 5 are energised by a multi-phase supply which is arranged at any one time to generate a stator field which permeates the armature diametrically in a chosen direction. The field is rotatable by appropriate energisation of coils 5. As described, the coils are arranged in a three-phase manner so that normal three-phase continuously varying currents would produce a continuously rotating field. Normally, however it is required that the motor be used to position a member and maintain it in that position. In order to do this it is necessary to arrest the rotation of the magnetic field when the required linear position of the armature has been reached.

The operation of the motor with annular projections shown in Figures 1 and 2 may be clearer from a consideration of Figure 3. This figure illustrates schematically only the helix 7 and the stator teeth 9. The two-start helix 7 is constituted by parts 7a and 7b and having regard to the protruding teeth 9 on the armature it will be seen that for a particular axial position of the armature with respect to the stator there are two diametrically opposed generators at which the teeth 9 are closest to the helix 7, the annular on which the teeth 9 are formed cross the helix namely where. These generators include positions of minimum relucatance and if a diametrical stator field is generated in a particular direction the tendency will be for the armature to move until the direction of the diameter between the said generators coincides with the direction of the field.

In Figure 3 the field direction is illustrated by arrows 10 and this corresponds to the equilibrium position shown where the positions of minimum reluctances are at the top and bottom of the armature. If now the stator field is rotated the armature will move axially so that positions of minimum reluctance follow the field. It will be appreciated that this action is synchronous and the motor has the characteristics of a synchronous motor. If the stator field is rotated too fast having regard to the inertia and load of the system being driven then the motor will be pulled out of synchronism. A complete cyclic rotation of the field corresponds to an armature movement of $4s$.

Referring now to Figure 4 there is illustrated diagrammatically an arrangement of armature and stator in accordance with the invention which differs from that shown in Figure 3. In Figure 4 the stator has a single-start helix 7 which is clockwise. Instead of annular ribs the armature has a helix 11 of the same tooth width and pitch as helix 7 but which is anti-clockwise. It will be seen that there are positions of minimum magnetic reluctance where the two helices are adjacent to each other and these positions lie along generators which are diametrically opposite. Axial movement of the armature with respect to the stator causes an effective rotation of these positions of minimum reluctance. Thus, the position of the armature corresponds to the direction of a diametrical stator field in the same way as in the embodiment of Figure 3. In Figure 4 the field direction for equilibrium in the position shown is, as illustrated, perpendicular to the plane of the paper.

The invention is clearly not limited to the particular dimensions and size of the motor but for purposes of illustration it may be pointed out that a motor has been constructed along the lines of that shown in Figures 1 and 2 which has the following characteristics. The spacing gap s is 1.22 mm. The positional accuracy is better than 0.025 mm, and the speed of response is about 5 cms. per second. The force available from the motor is up to 10 kg. and the holding force is about 10^5 N/m. The sytem for energising the windings is capable of adjustment in frequency from 0Hz to about 20Hz. Alternatively, however, higher frequencies may be used, particularly if the stator and armature are laminated or composed of low-loss materials such as ferrites.

WHAT WE CLAIM IS:—

1. A linear electric motor comprising a first cylindrical member provided with windings which may be energised to produce a magnetic field perpendicular to the longitudinal axis of the member and controllable in direction and a second cylindrical member inside or outside the first member; there being an air-gap between the members and the members being axially movable with respect to each other, one of the members having a magnetically salient helix and the other member having, in axial section, magnetic projections adjacent the helix, which projections follow a path or paths in the second member, the arrangement being such that the path or

paths and the helix cross so that the spacing between the projections and the helix varies around the air-gap and is least at points along one or more pairs of diametrically opposed generators (as herein defined), the positions of which generators depend on the relative axial positions of the members.

2. A linear electric motor as claimed in claim 1 wherein the magnetic projections are constituted by annular ribs separated by annular grooves and the helix has an even number of starts.

3. A linear electric motor as claimed in claim 1 wherein the magnetic projections are constituted by a second magnetically salient helix of opposite hand to the first, and means are provided for preventing, during operation, relative rotation of the two members.

4. A linear electric motor as claimed in claim 3 wherein means are provided for rotating one member relative to the other member at will to determine a zero position at which the members may be locked against further relative rotation.

5. A linear electric motor as claimed in any of claims 2 to 4 wherein the axial spacing of the magnetic projections is s; the minimum width of the air-gap is g; and the ratio s/g is between 2.5 and 4.

6. A linear electric motor substantially as hereinbefore described with reference to any of the accompanying drawings.

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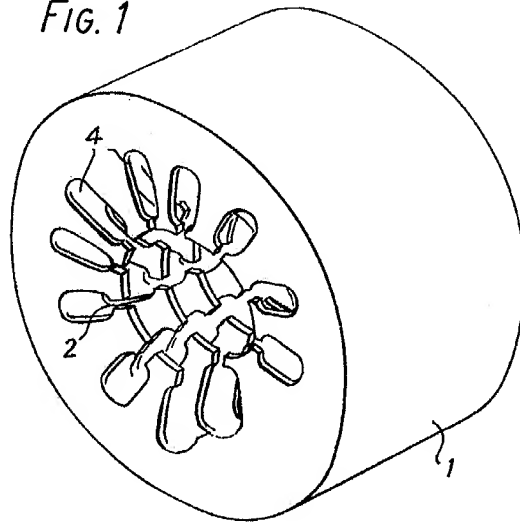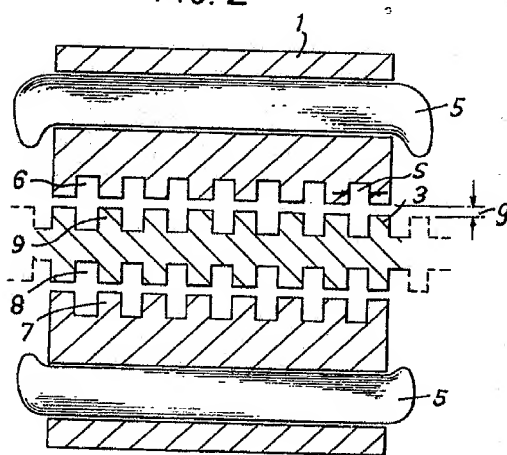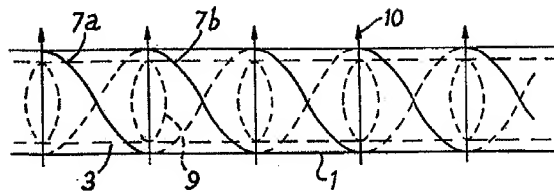London W.C.2.

FIG. 1

FIG. 2

FIG. 3

FIG. 4